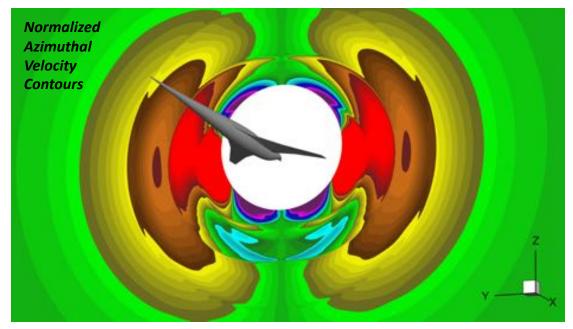
Efficient Near-Field to Mid-Field Sonic Boom Propagation using a High-Order Space Marching Method*



*funded by the NASA's ARMD Commercial Supersonic Technologies (CST) project

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Introduction



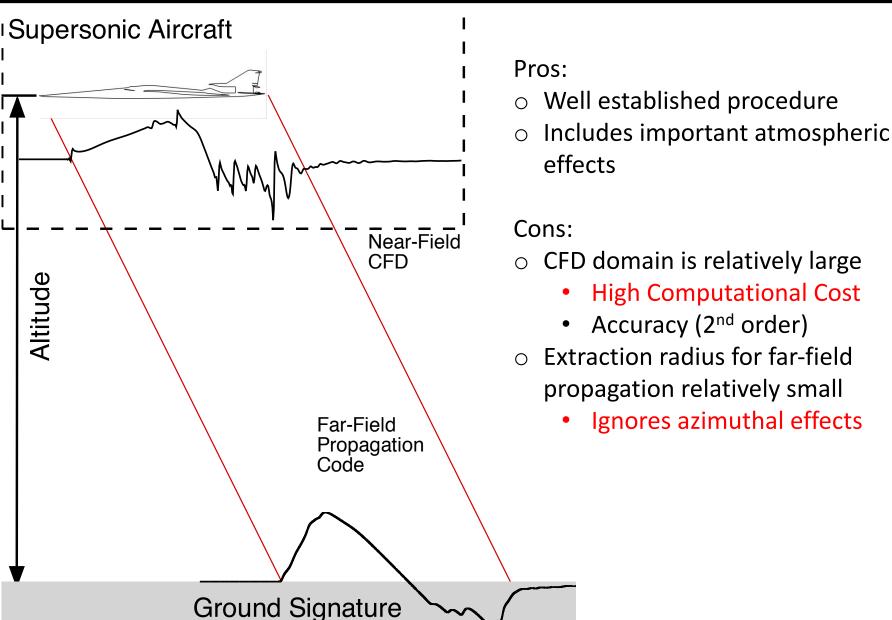
NASA's Low-Boom Flight Demonstration (LBFD) project

- Primary goal is to demonstrate feasibility of supersonic over-land flight at reduced loudness levels
- X-59 Quiet Supersonic Technology (QueSST) airplane
 - 94 ft. long and 29.5 ft. wide single jet engine aircraft
 - Designed to fly at Mach 1.42 at 55,000 ft.
- Mission planning requires large database consisting of O(1000)-O(10,000) solutions
 - High Computational Resources
 - Must be automated
 - Must be accurate

Iso-parametric view

2-Step Ground Level Noise Prediction

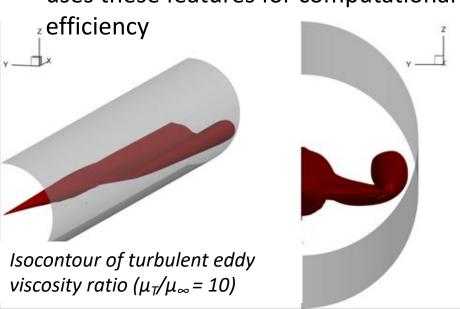


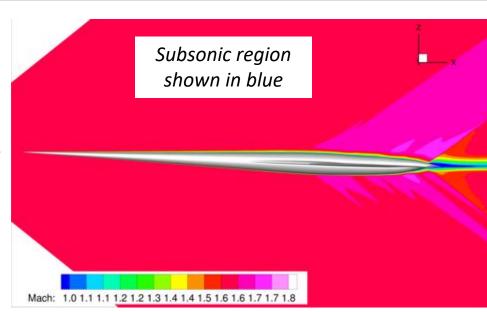


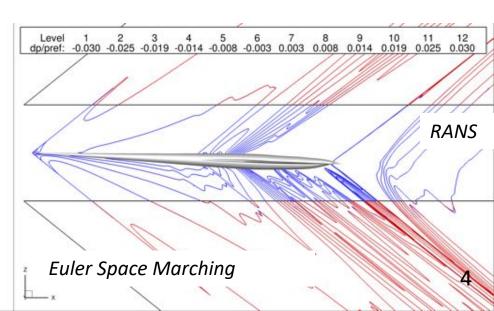
Special Features of Supersonic Flow



- All information travels in a common "time-like" direction along characteristic surfaces
- Viscous effects are only important near the walls of the aircraft
- Space marching is a special discretization/solution strategy which uses these features for computational

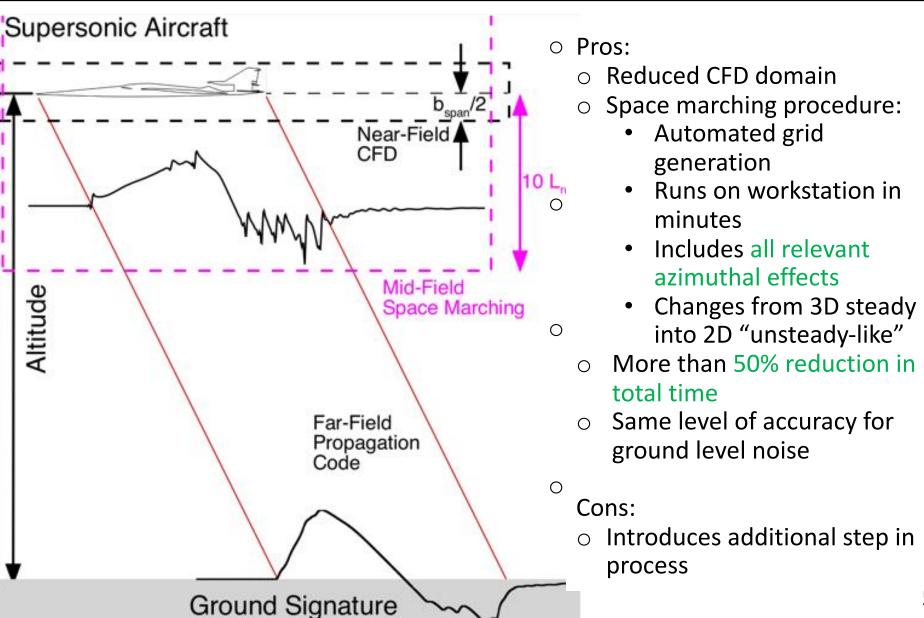






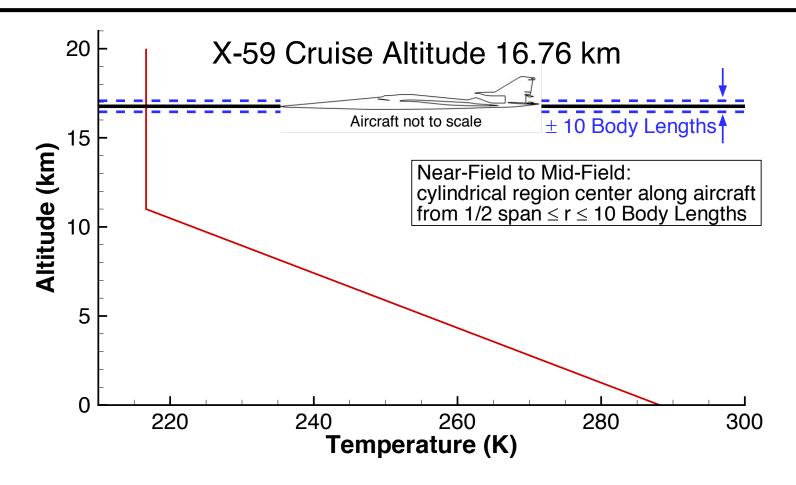
3-Step Ground Level Noise Prediction





Definition of Near-Field to Mid-Field

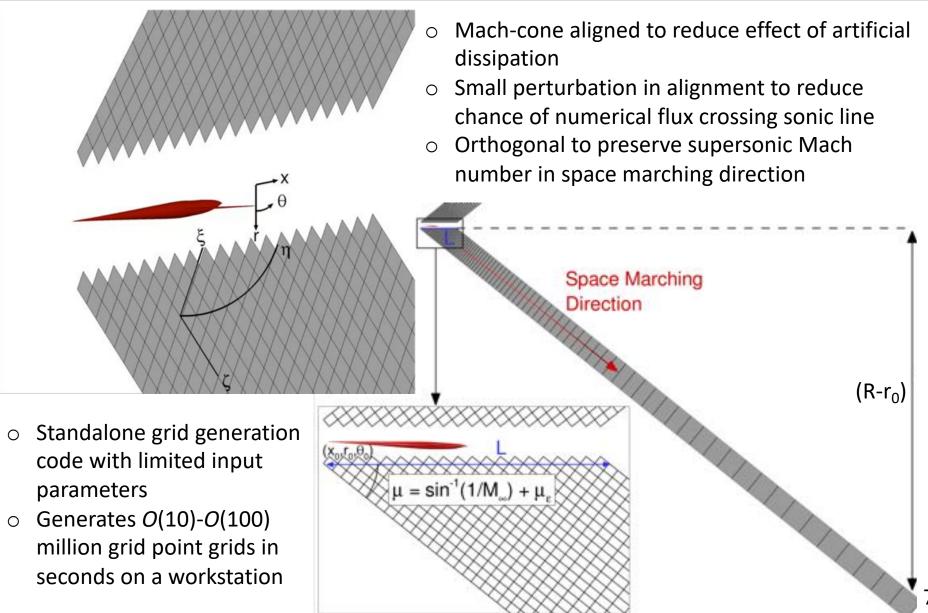




- Plot of altitude versus ICAO standard atmospheric temperature
- No variation in temperature within 10+ body lengths of the aircraft
- Atmospheric effects are neglected in the current approach
 - examples: wind variation, molecular relaxation, and humidity

Mach-cone Aligned Space Marching Grid

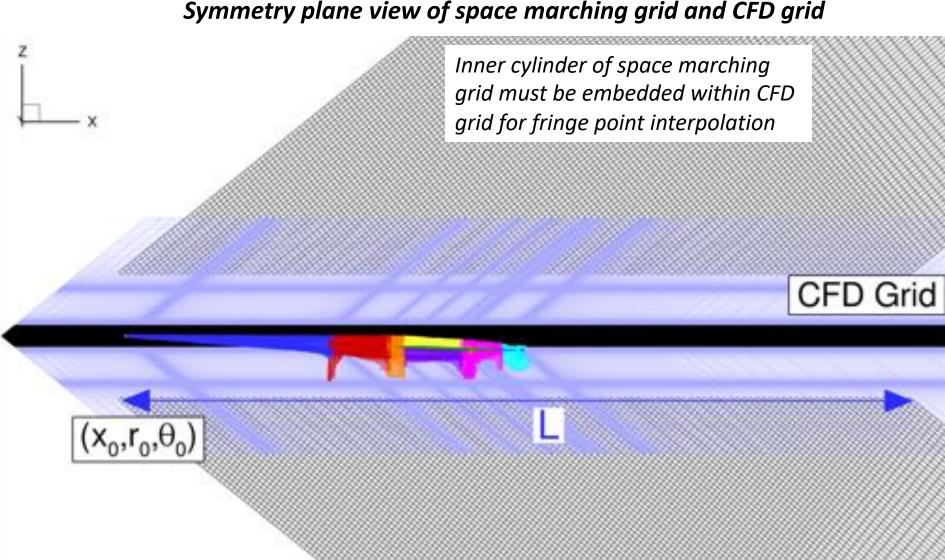




Mach-cone Aligned Space Marching Grid



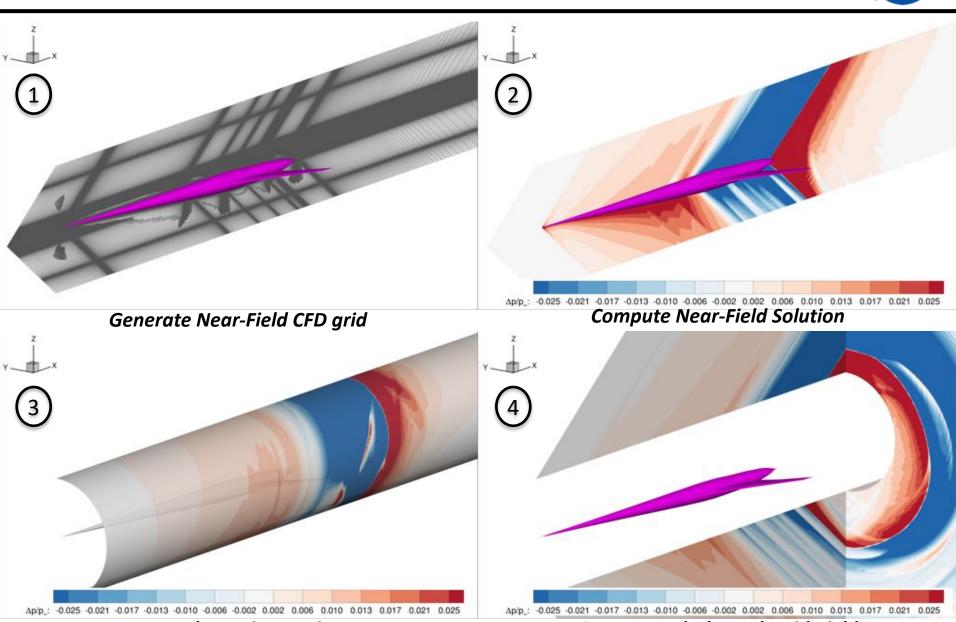
Symmetry plane view of space marching grid and CFD grid



Space Marching Grid

Near-Field to Mid-Field Procedure





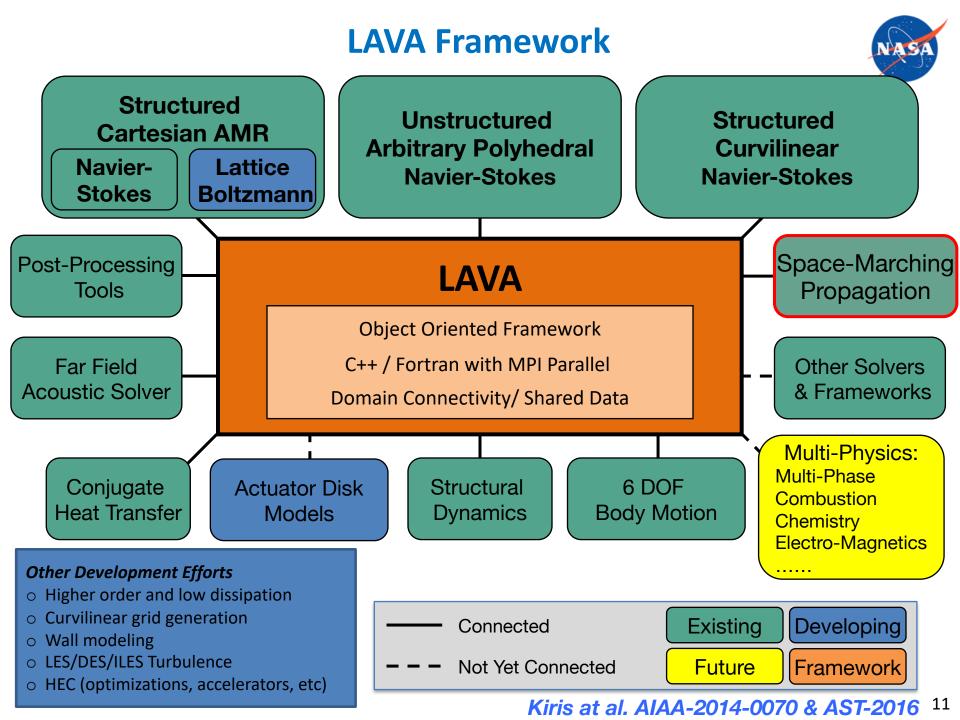
Interpolate Fringe Points

Space March through Mid-Field

Numerical Discretization (Space Marching Propagation)



- Governing equations are the steady-state 3D Euler equations transformed to a general curvilinear coordinate system in strong conservation law form
- Second-order BDF2 is used in the space marching direction
- High-order Hybrid Weighted Compact Nonlinear Scheme (HWCNS) is used in the other two coordinate directions
 - Interface (half-point) fluxes are evaluated with modified Roe
 - Left/Right interface states use 3rd or 5th order WENO interpolation
 - 4th order centered finite difference using a combination of fluxes at the grid points and the half-points
- Identical finite-difference operators (BDF2 and HWCNS) used in metric term evaluation for free-stream preservation
- 2D nonlinear system is solved at each space marching station using an alternating line Jacobi relaxation



Computational Results



JAXA Wing Body

- Sensitivity Studies: (see paper for all sensitivity studies)
 - Mach cone perturbation angle
 - Stretching ratio
 - Maximum aspect ratio
 - Streamwise resolution
 - Circumferential resolution

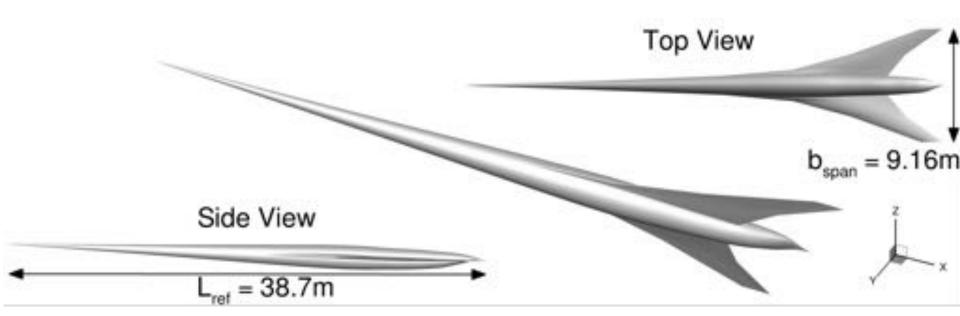
- Circumferential extent
- Metric term evaluation
- Convective flux discretization
- Nonlinear convergence tolerance
- Azimuthal Dependence of Nonlinear Wave Propagation
 - Near-Field to Mid-Field
 - Mid-Field to Ground
- Low Boom Aircraft Wind Tunnel Model
 - Space Marching Grid and Solution
 - Wind Tunnel Comparison

JAXA Wing Body



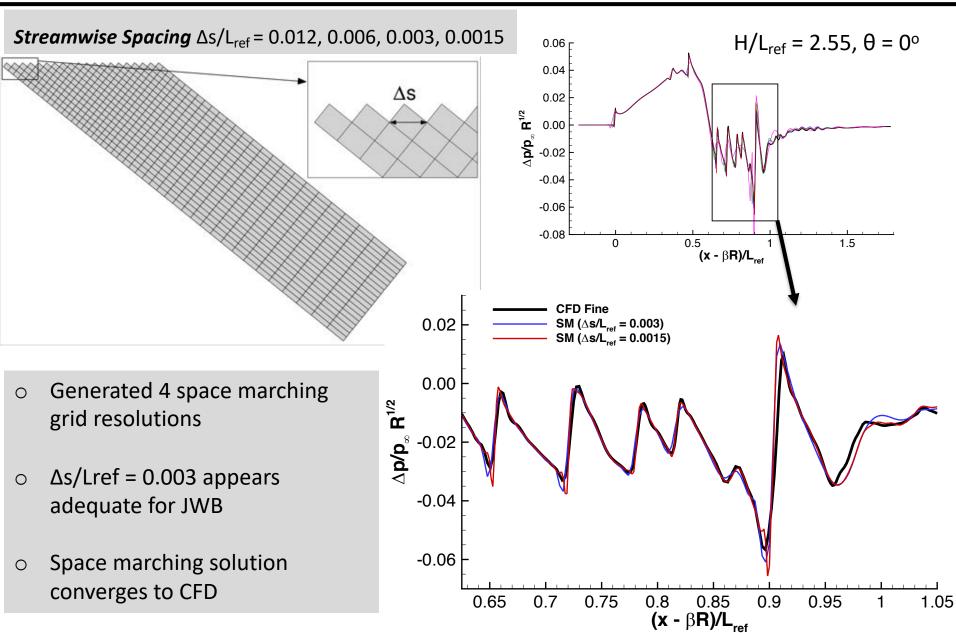
JAXA Wing Body (JWB) configuration from 2^{nd} AIAA Sonic Boom Workshop (SBPW2)

- Designed to achieve low boom levels
- Reference length: L_{ref} = 38.7 m
- O Mach = 1.6, Re/m = 5.7 million, and α = 2.3°
- Near-field CFD results using LAVA reported at SBPW2



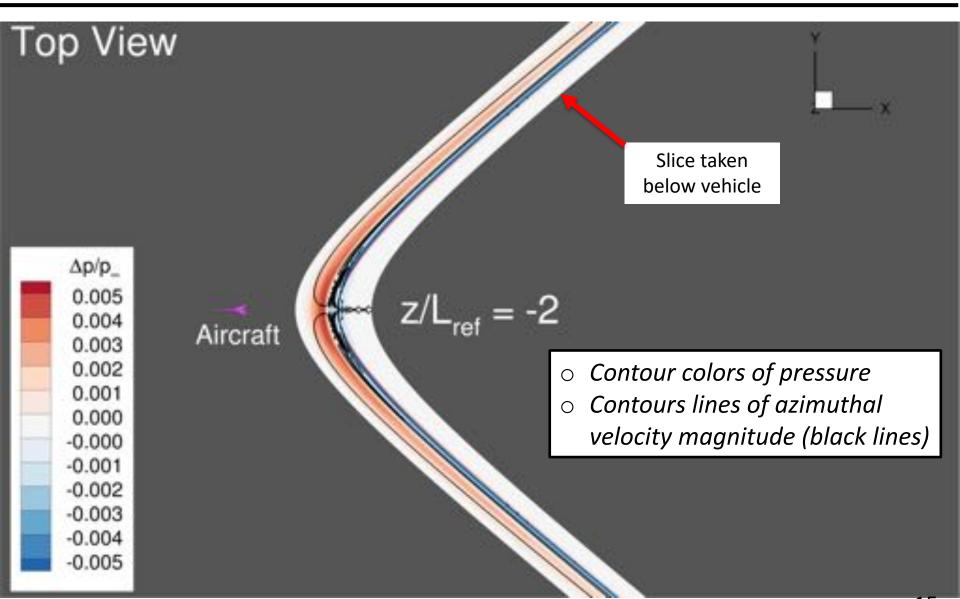
Sensitivity Study (Streamwise Spacing)





Azimuthal Dependence of Nonlinear Wave Propagation

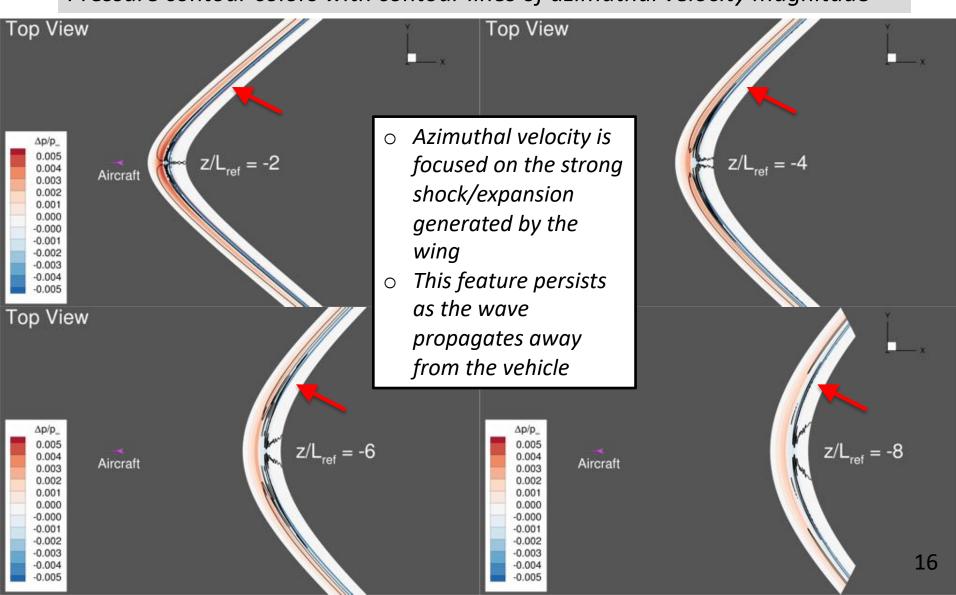




Azimuthal Dependence of Nonlinear Wave Propagation



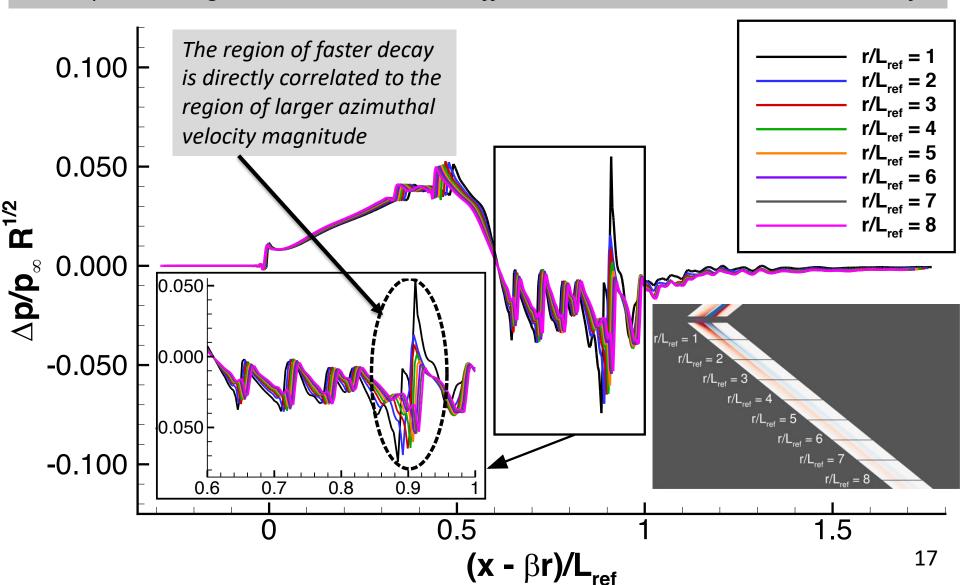
Pressure contour colors with contour lines of azimuthal velocity magnitude



Azimuthal Dependence: Near-Field to Mid-Field



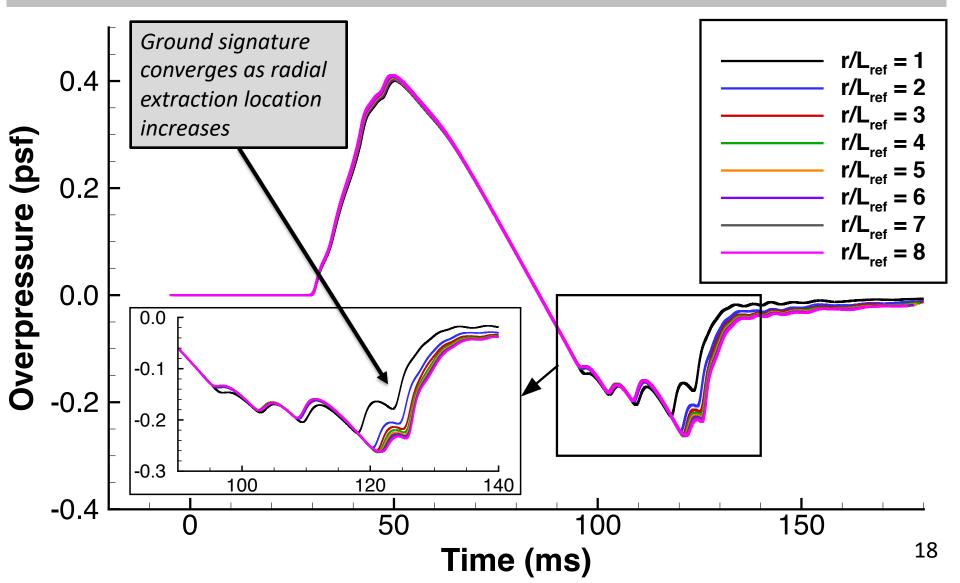
Scaled pressure signatures extracted at 8 different radial locations below the aircraft



Azimuthal Dependence: Mid-Field to Ground



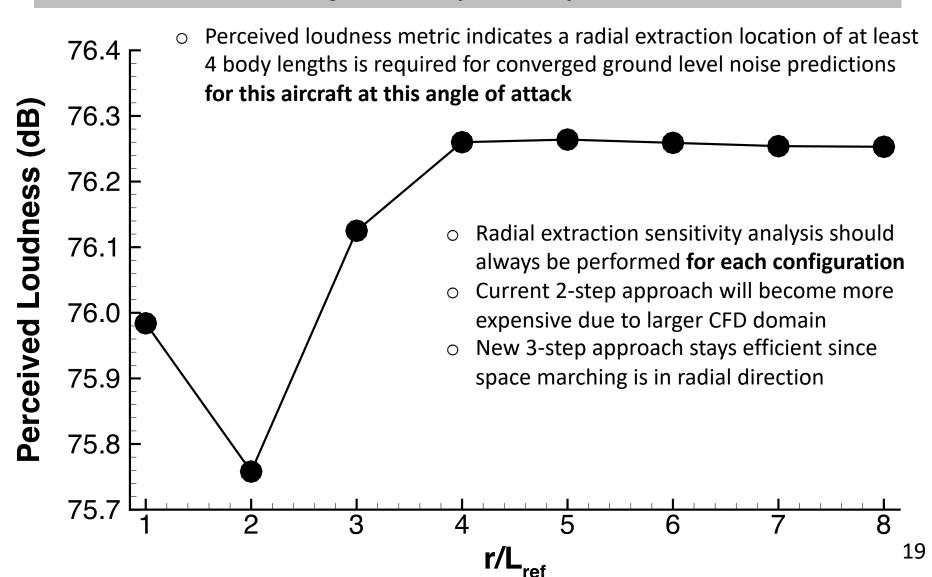
Overpressure ground signatures propagated with sBOOM from each radial extraction



Azimuthal Dependence: Mid-Field to Ground



Perceived loudness on the ground as a function of radial extraction location



Low Boom Aircraft Wind Tunnel Model



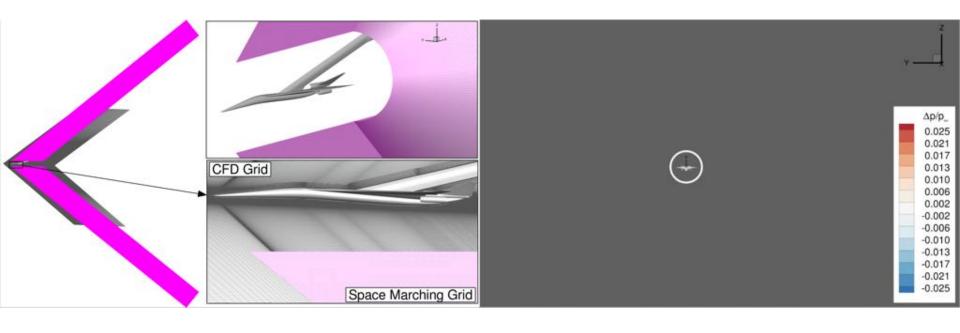
Lockheed Martin Phase I low boom model from 1st AIAA Sonic Boom Workshop (LM1021)

- Designed to achieve low boom on-track signatures
- \circ Reference length: L_{ref} = 22.365 inch (0.568 m) 0.008 percent scale
- \circ Mach = 1.6, Re/m = 4.36 million, and α = 2.1°
- Experimental data reported in Cliff et. al. (AIAA-2014-0560)
- Near-field CFD results using LAVA reported in Housman et. al. (AIAA-2014-2008)



LM1021 Space Marching Grid and Solution

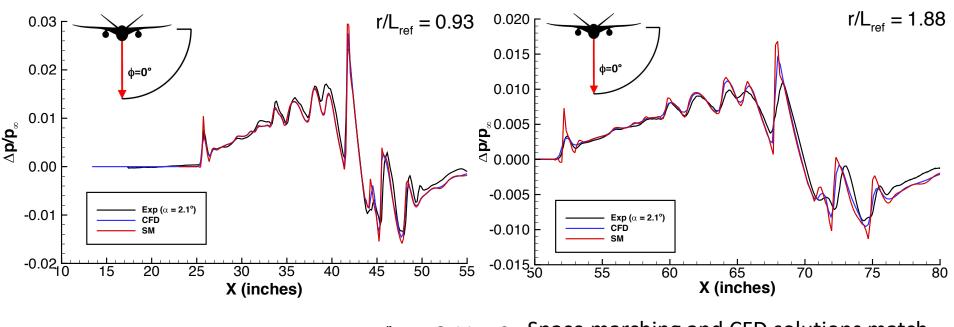


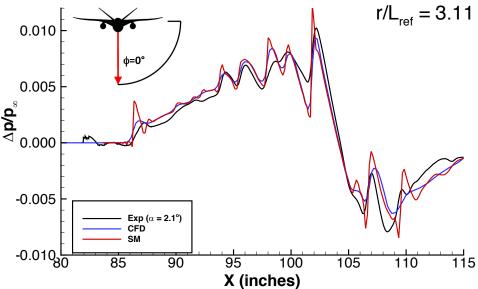


- Inputs for space marching grid generation were taken from grid sensitivity studies (see paper for details)
- \circ SR = 1.05, AR_{max} = 20, Δs/L_{ref} = 0.003, Δθ = 1°, θ_{max} = 180°, R = 10 L_{ref}
- Grid Dimensions: 351 x 181 x 564 (35.8 Million points, 4.2 seconds to generate)
- Inputs for space marching solver parameters were taken from solver sensitivity study (HWCNS4-ZWENO5)
- Space marching wall-clock time 106 seconds using 80 threads on single workstation

LM1021 Wind Tunnel Comparison







- Space marching and CFD solutions match wind tunnel data well at r/L_{ref} = 0.93
- As r/L_{ref} increases pressure peaks in wind tunnel data appear smoothed (averaging procedure see Cliff 2014)
- Space marching and CFD solutions retain sharp peaks at larger r/L_{ref}
- Space marching solution shows higher amplitudes than 2nd order CFD

Computational Savings



Example: JAXA Wing Body (66% reduction)

Measured Time (JWB)	2-Step Approach	3-Step Approach
CFD (RANS)	1920 core hrs. (R = 7L _{ref})	640 core hrs. (R ~ b/2)
Space Marching*	NA	3 min. 6 seconds (R = 10L _{ref})
sBOOM (1 azimuth)	~30 seconds	~30 seconds
Total Time	1920 hrs. 30 sec.	640 hrs. 3 min. 36 sec.

- o Total time dominated by near-field CFD with both approaches
- Reduction of CFD domain extend lead to the reduction in total time
- Space marching approach time is small:
 - Space marching grid generation (116.4 Million points 13.6 sec.)
 - Interpolation of CFD solution onto fringe points (7.5 sec. 40 cores)
 - Space marching solution (164.9 sec. 80 threads)

Summary



- A high-order accurate space marching method was developed for efficient near-field to mid-field sonic boom propagation
 - A Mach-cone aligned curvilinear grid using iblanking technology was developed which is appropriate for space marching
 - Thorough grid and solver parameter sensitivity studies reported in paper
 - Important azimuthal effects on near-field to mid-field wave propagation and mid-field to ground level noise prediction was demonstrated
 - Completed validation of the near-field to mid-field approach on the LM1021 wind tunnel model
- o A three-stage process for computing ground level noise from an aircraft was developed
 - Reduces CFD domain extent by 40 60 %
 - Introduces new near-field to mid-field space marching method
 - Space marching grid generated in seconds (automatically)
 - Interpolation from CFD to space marching grid
 - Space marching propagation (up to 10 body lengths) in minutes on a workstation
 - Total time reduction of 66% compared to current approach for the JAXA wing body configuration